Gravitational Leptogenesis and Neutrino Mass Limit

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Recently Davoudiasl *et al* [1] have introduced a new type of interaction between the Ricci scalar R and the baryon current J^μ, $\partial_\mu R J^\mu$ and proposed a mechanism for baryogenesis, the gravitational baryogenesis. Generally, however, $\partial_\mu R$ vanishes in the radiation dominated era. In this paper we consider a generalized form of their interaction, $\partial_\mu f(R) J^\mu$ and study again the possibility of gravitational baryo(lepto)genesis. Taking $f(R) \sim \ln R$, we will show that $\partial_\mu f(R) \sim \partial_\mu R/R$ does not vanish and the required baryon number asymmetry can be *naturally* generated in the early universe.

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The origin of the baryon number asymmetry remains a big puzzle in cosmology and particle physics. Conventionally, it is argued that this asymmetry is generated from an initial baryon symmetric phase dynamically as long as the following conditions are satisfied [2]: (1) baryon number non-conserving interactions; (2) C and CP violations; (3) out of thermal equilibrium. When the CPT is violated dynamically, however the baryon number asymmetry can be generated in thermal equilibrium [3]. In connecting to dark energy recently we have studied a class of models of spontaneous baryo(lepto)genesis [4, 5] [1] by introducing a interaction between the dynamical dark energy scalars and the ordinary matter. Specifically, we have considered a derivative coupling of the quintessential scalar field Q to the baryon or lepton current,

$$\mathcal{L}_{int} \sim \partial_\mu Q J^\mu \ . \tag{1}$$

One silent feature of this scenario for baryogenesis is that the present accelerating expansion and the generation of the matter and antimatter asymmetry of our universe is described in a unified way.

Recently, Davoudiasl *et al* [1] proposed a new mechanism (dubbed gravitational baryogenesis) of generating baryon asymmetry in thermal equilibrium. They introduced explicitly an interaction between the Ricci scalar curvature with derivative and the baryon number current:

$$\mathcal{L} = \frac{1}{M^2} \partial_\mu R J^\mu \ . \tag{2}$$

And the baryon number asymmetry is given by

$$\frac{n_B}{s} \sim \frac{\dot{R}}{M^2 T} \ , \tag{3}$$

which shows that n_B/s is determined by the value of $\dot{R}$, however the Einstein equation, $R = 8\pi G T^\mu_\mu = 8\pi G (1 - 3w)\rho$, tells us that $\dot{R} = 0$ in the radiation-dominated epoch of the standard Friedmann-Robertson-Walker (FRW) cosmology. Davoudiasl *et al* in Ref. [1] have considered three different possibilities of obtaining a non-vanishing $\dot{R}$ which include the effects of trace anomaly, reheating and introducing a non-thermal component with $w > 1/3$ dominant in the early universe. In the braneworld scenario Shiromizu and Koyama in Ref. [7] provided another example for $\dot{R} \neq 0$.

In this paper we propose a generalized form of the derivative coupling of the Ricci scalar to the ordinary matter:

$$\mathcal{L}_{int} \sim \partial_\mu f(R) J^\mu \ , \tag{4}$$

then study the possibility of gravitational baryo(lepto)genesis. In Eq. (4), $f(R)$ is a function of R and for a detailed study in this paper we take explicitly $f(R) \sim \ln R$. So we have now an effective Lagrangian

$$\mathcal{L}_{int} = -c \frac{\partial_\mu R}{R} J^\mu \ . \tag{5}$$

This type of operators is expected by integrating out the heavy particles or extra dimension [8, 9] and the coefficient c characterizes the strength of this new interaction in the effective theory. In Refs. [8, 9] effective operators like $1/(R^m)$

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[1] For related studies, see [6]

(with $m > 0$) have been considered for the purpose of modifying the Einstein gravity and dynamically solving the cosmological constant problem. In this paper we will show that within the framework of the standard FRW cosmology, our model with $\mathcal{L}_{int}$ in (5) can naturally generate the baryon number asymmetry in the early universe.

Taking $J^\mu = J_B^\mu$, during the evolution of the spatial flat FRW universe, $\mathcal{L}_{int}$ in Eq. (5) gives rise to an effective chemical potential μ_b for baryons:

$$-\frac{c}{R}\partial_\mu R \, J^\mu \rightarrow -c\frac{\dot{R}}{R}n_B = -c\frac{\dot{R}}{R}(n_b - n_{\bar{b}}) \;,$$

$$\mu_b = -c\frac{\dot{R}}{R} = -\mu_{\bar{b}} \;. \tag{6}$$

In thermal equilibrium, the net baryon number density doesn't vanish as long as $\mu_b \neq 0$ (when $T \gg m_b$) [10]:

$$n_B = \frac{g_b T^3}{6\pi^2}[\pi^2(\frac{\mu_b}{T}) + (\frac{\mu_b}{T})^3] \;, \tag{7}$$

where g_b is the number of intrinsic degrees of freedom of the baryon. The final ratio of the baryon number to entropy is

$$\left.\frac{n_B}{s}\right|_{T_D} \simeq -\frac{15g_b}{4\pi^2 g_{*s}}\left.\frac{c\dot{R}}{RT}\right|_{T_D} \;, \tag{8}$$

where the cosmic entropy density is $s = \frac{2\pi^2}{45}g_{*s}T^3$ and g_{*s} counts the total degrees of freedom of the particles which contribute to the entropy of universe. T_D in (8) is the freezing out temperature of baryon number violation.

$\dot{R}/R$ in (8) can be obtained from the Einstein equation. For a constant equation of state of the fluid which dominates the universe, one has

$$\frac{\dot{R}}{R} = -3H(1 + w) \;. \tag{9}$$

Hence, in the radiation-dominant epoch, $w = 1/3$, and we have:

$$\frac{\dot{R}}{R} = -4H = -6.64g_*^{1/2}\frac{T^2}{m_{pl}} \;. \tag{10}$$

In the equation above we have used $H = \sim 1.66g_*^{1/2}T^2/m_{pl}$, and g_* counts the total degrees of freedom of effective massless particles. For most of the history of the universe all particle species had a common temperature, and g_* is almost the same as g_{*s}, so, in the following, we will not distinguish between them.

Substituting (10) into (8) we arrive at a final expression of the baryon number asymmetry:

$$\left.\frac{n_B}{s}\right|_{T_D} = \frac{15}{\pi^2}\frac{cg_b H(T_D)}{g_* T_D}$$

$$\simeq 2.52cg_b g_*^{-1/2}\frac{T_D}{m_{pl}} \sim 0.1c\frac{T_D}{m_{pl}} \;. \tag{11}$$

In the numerical calculations above, we have used $g_b \sim \mathcal{O}(1)$ and $g_* \sim \mathcal{O}(100)$. Taking $c \sim \mathcal{O}(1)$, $n_B/s \sim 10^{-10}$ requires the decoupling temperature T_D to be in the order of:

$$T_D \sim 10^{-9}m_{pl} \sim 10^{10} \text{ GeV} \;. \tag{12}$$

A value of T_D at or larger than 10^{10} GeV can be achieved in theories of grand unification easily, however, if the B-violating interactions conserve $B - L$, the asymmetry generated will be erased by the electroweak Sphaleron [11]. In this case T_D will be as low as around 100 GeV and n_B/s generated will be of the order of 10^{-18}. Hence, now we turn to leptogenesis [12, 13]. We take J^μ in Eq. (5) to be J_{B-L}^μ. Doing the calculations with the same procedure as above for $J^\mu = J_B^\mu$ we have the final asymmetry of the baryon number minus lepton number

$$\left.\frac{n_{B-L}}{s}\right|_{T_D} \sim 0.1c\frac{T_D}{m_{pl}}. \tag{13}$$

The asymmetry n_{B-L} in (13) will be converted to baryon number asymmetry when electroweak Sphaleron $B + L$ interaction is in thermal equilibrium which happens for temperature in the range of 10^2 GeV $\sim 10^{12}$GeV. T_D in (13) is the temperature below which the $B - L$ interactions freeze out.

In the Standard Model of the electroweak theory, $B - L$ symmetry is exactly conserved, however many models beyond the standard model, such as Left-Right symmetric model predict the violation of the $B - L$ symmetry. In this paper we take an effective Lagrangian approach and parameterize the $B-L$ violation by higher dimensional operators. There are many operators which violate $B - L$ symmetry, however at dimension 5 there is only one operator[2],

$$\mathcal{L}_{\not L} = \frac{2}{f} l_L l_L \chi\chi + \text{H.c.} , \tag{14}$$

where f is a scale of new physics beyond the Standard Model which generates the $B - L$ violations, l_L and χ are the left-handed lepton and Higgs doublets respectively. When the Higgs field gets a vacuum expectation value $< \chi > \sim v$, the left-handed neutrino receives a majorana mass $m_\nu \sim \frac{v^2}{f}$.

In the early universe the lepton number violating rate induced by the interaction in (14) is [16]

$$\Gamma_{\not L} \sim 0.04 \, \frac{T^3}{f^2} . \tag{15}$$

Since $\Gamma_{\not L}$ is proportional to T^3, for a given f, namely the neutrino mass, $B - L$ violation will be more efficient at high temperature than at low temperature. Requiring this rate be larger than the Universe expansion rate $\sim 1.66 g_*^{1/2} T^2/m_{pl}$ until the temperature T_D, we obtain a T_D-dependent lower limit on the neutrino mass:

$$\sum_i m_i^2 = (0.2 \text{ eV}(\frac{10^{12} \text{ GeV}}{T_D})^{1/2})^2 . \tag{16}$$

Taking three neutrino masses to be approximately degenerated, i.e. , $m_1 \sim m_2 \sim m_3 \sim \bar m$ and defining $\Sigma = 3\bar m$, one can see that for $T_D \sim 10^{10}$ GeV, three neutrinos are expected to have masses $\bar m$ around $\mathcal{O}(1 \text{ eV})$. The current cosmological limit comes from WMAP [17] and SDSS [18]. The analysis of Ref. [17] gives $\Sigma < 0.69$ eV. The analysis from SDSS shows, however that $\Sigma < 1.7$ eV [18]. These limits on the neutrino masses requires T_D be larger than 2.5×10^{11} GeV or 4.2×10^{10} GeV. The almost degenerate neutrino masses required by the leptogenesis of this model will induce a rate of the neutrinoless double beta decays accessible for the experimental sensitivity in the near future [19]. Interestingly, a recent study [20] on the cosmological data showed a preference for neutrinos with degenerate masses in this range.

The experimental CPT test with a spin-polarized torsion pendulum [21] puts strong limits on the axial vector background b_μ defined by $\mathcal{L} = b_\mu \bar e \gamma^\mu \gamma_5 e$ [22]:

$$|\vec b| \leq 10^{-28} \text{ GeV} . \tag{17}$$

For the time component b_0, the bound is relaxed to be at the level of 10^{-25} GeV [23]. In our model, assuming the Ricci scalar couples to the electron axial current the same as Eq. (5), we can estimate the CPT-violation effect on the laboratory experiments. For a spatial-flat universe with a constant equation of state of the dark energy w_X, one has

$$\frac{\dot R}{R} = -3H[1 + \frac{w_X(1 - 3w_X)\Omega_X}{1 - 3w_X\Omega_X}] \sim -H , \tag{18}$$

thus the current value of $\frac{\dot R_0}{R_0}$ is about $\sim -H_0$, and the induced CPT-violating b_0 is

$$b_0 \sim -c\frac{\dot R_0}{R_0} \sim H_0 \leq 10^{-42} \text{ GeV} , \tag{19}$$

which is much below the current experimental limits.

In summary we have proposed a new type of interactions between the Ricci scalar and the ordinary matter, and studied the possibility of gravitational baryo(lepto)genesis. Our model can naturally explain the baryon number asymmetry $n_B/s \sim 10^{-10}$ without conflicting with the experimental tests on CPT.

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[2] Introducing a interaction between the dimension 5 operator in (14) and the Ricci scalar will induce the variation of the neutrino masses during the evolution of the universe, however the effect is negligible in this case [14, 15].

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